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## Period – mass-loss rate relation of Miras with and without Tc

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**Abstract.** We present the discovery that Mira variables separate in two distinct sequences in a near- to mid-IR color versus pulsation period diagram, if a distinction is made with respect to the presence of technetium (Tc) in the stars. Tc is an indicator of recent or ongoing deep mixing during a third dredge-up event. At a given period, the Tc-poor Miras are redder in  $K - [22]$  (i.e. have higher dust mass-loss rate) than the Tc-rich Miras. This is counter-intuitive since the Tc-rich Miras are expected to be more evolved and should have a higher mass-loss rate. In this contribution we give an update on this recently discovered conundrum.

### 1. The phenomenon

Figure 1 presents the phenomenon discovered by Uttenthaler (2013). The figure shows a diagram of the  $K - [22]$  color of Miras versus their pulsation period.  $[22]$  is the magnitude in the  $22\mu\text{m}$  band of the WISE space observatory, and the near- to mid-infrared color  $K - [22]$  is an indicator of the dust mass-loss rate ( $\dot{M}_{\text{dust}}$ ) of the stars. It is related to the total mass-loss rate via the gas-to-dust ratio  $\delta$ . Stars in Fig. 1 are marked according to their Tc content. Tc is an element with only radioactive isotopes that is produced by the s-process in the deep interior of AGB stars. It is an indicator of recent or ongoing third dredge-up (3DUP), a deep mixing event taking place in AGB stars.

The diagram in Fig. 1 clearly shows that the Tc-poor (open symbols) and the Tc-rich (filled) Miras occupy different regions, each of the two groups forming a sequence of increasing  $K - [22]$  with increasing period. The counter-intuitive aspect is that at a given period, the Tc-poor Miras have a *redder*  $K - [22]$  color than the Tc-rich ones, indicating a higher dust mass-loss rate. This is not what one would naïvely expect because the Tc-rich Miras are more evolved than the Tc-poor ones, a phase when also the (dust) mass-loss rate is expected to be higher. This figure demonstrates that this simple picture must be wrong. Note that this phenomenon is not inherent to the  $[22]$  band; mid-IR bands ranging from AKARI [9] to IRAS [60] were investigated, too, all of which show the same two sequences.

There are a few objects that blur the otherwise clear separation between Tc-poor and Tc-rich Miras in that diagram. There are two Tc-rich, M-type Miras (filled black squares) at  $P \approx 330$  d and  $\approx 390$  d and  $K - [22] \approx 3.5$ . These are o Cet and R Aqr, both of which are well-known binary AGB stars. The reddest S-type Mira (blue triangle), at  $P \approx 490$  and  $K - [22] \approx 4.0$ , is W Aql, also a binary AGB star. It seems that binary AGB stars are particularly red for their period. Possibly, the presence of a companion to an extended red giant star enhances either the dust production in the system or the

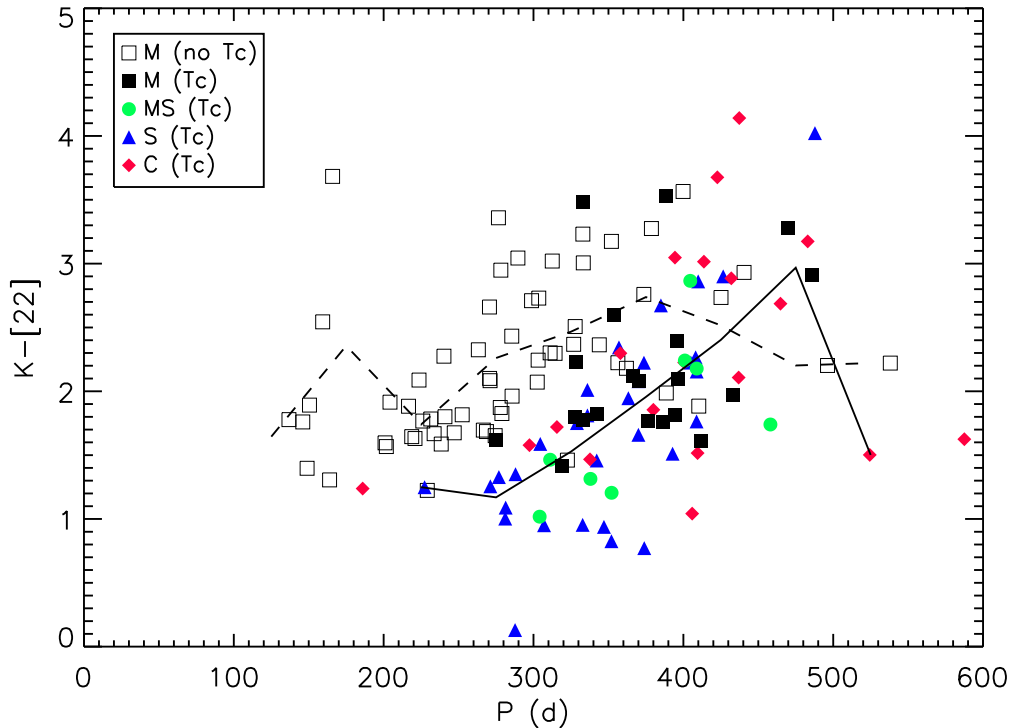


Figure 1. Mira stars of different atmospheric chemistry (spectral type) in the  $K - [22]$  vs.  $P$  diagram. Empty symbols are for Tc-poor, filled symbols are for Tc-rich stars. The dashed line indicates the run of the mean  $K - [22]$  color in 50 d period bins for the Tc-poor stars, while the solid line shows this run for the Tc-rich stars. Taken from Uttenthaler (2013).

(dust) mass-loss rate from the system. There is a very red, Tc-poor Mira (open square) at  $P \approx 165$  d, which is R Cet. We tentatively predict that this is a binary star, too.

On the other hand, there are Tc-poor Miras at long period, but relatively blue  $K - [22]$  color. The Tc-poor Miras with the longest pulsation period in the sample are R Nor and R Cen, both of which have been suggested to be massive AGB stars ( $M \gtrsim 4M_{\odot}$ ). The dominant neutron source in these stars is from the  $\alpha$ -capture on  $^{22}\text{Ne}$ , which is predicted to produce only very little Tc (García-Hernández et al. 2013). A similar case could be W Hya, at  $P \approx 390$  d and  $K - [22] \approx 2.0$ , which has also been speculated to be of relatively high mass.

We also investigated the distribution of semi-regular variables (SRVs) in that diagram, in particular the Tc-rich ones. A sequence of increasing mass-loss rate with increasing period is formed by mainly S- and C-type SRVs at short periods ( $0 < P \lesssim 200$  d) and rather blue colors ( $K - [22] \lesssim 1.2$ ). It is possible that some of the SRVs at the top of this sequence switch to overtone pulsation, i.e. to the Mira phase, and continue their evolution there. However, this seems to be possible only for the S- and C-type stars, not for the M-type stars.

Also, there are a few SRVs with much redder  $K - [22]$  color than the mentioned sequence. Some of these stars are suspected or known binaries (e.g.  $\pi^1$  Gru, L<sup>2</sup> Pup),

which leads one to suspect that also in this group the binarity has a considerable effect on the (dust) mass-loss rate.

## 2. ISO dust spectra

It is instructive to also inspect the dust spectra of Miras with and without Tc. Spectra of AGB stars in the mid-IR have been observed by ISO and processed and published by Sloan et al. (2003b). Unfortunately, there is not much overlap between the ISO sample and the sample of AGB stars with known Tc content discussed here. Nevertheless, already the few stars in common show interesting things. Figure 2 shows a comparison of the ISO spectra of the Tc-poor Mira RR Aql and the Tc-rich star R Hya. As shown in the figure legend, the two Miras have very similar pulsation periods, but quite different  $K - [22]$  colors.

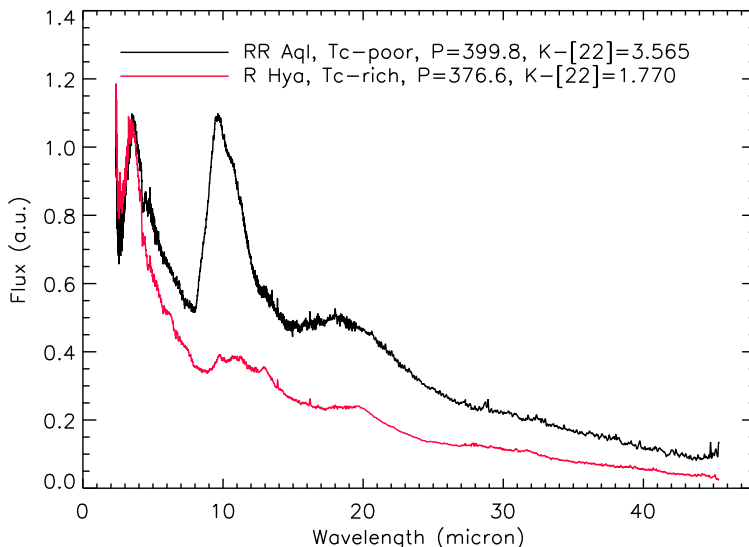


Figure 2. ISO dust spectra of the stars RR Aql (Tc-poor, black line) and R Hya (Tc-rich, red line). The spectra are normalised to a mean of 1.0 in the range between 3 and 4  $\mu\text{m}$ .

The spectra of the Tc-rich Miras S Vir and T Cep, also with very similar pulsation periods, look very similar to R Hya. Clearly, the Tc-poor and Tc-rich Miras are distinctly different also in the ISO dust spectra, with the Tc-rich stars having a much lower mid-IR dust excess than the Tc-poor ones over a wide wavelength range.

Sloan et al. (2003a) investigated the appearance of the 13  $\mu\text{m}$  feature in the ISO sample and its correlation to other dust features and stellar parameters. This feature is also visible in the spectra of some of the Tc-rich Miras, but a clear correlation is not obvious in the small overlap sample. Nevertheless, within each of the groups “Tc-poor Miras”, “Tc-rich Miras”, and “Tc-rich SRVs”, the sources showing the 13  $\mu\text{m}$  feature are the bluest ones, and those without the 13  $\mu\text{m}$  feature are the reddest ones in  $K - [22]$  (there is only one Tc-poor SRV with an ISO spectrum). This lends support to the conclusion of Sloan et al. (2003a) that the 13  $\mu\text{m}$  feature is stronger in objects with lower IR excess and thus lower mass-loss rates. Hence, the 13  $\mu\text{m}$  feature in Tc-

rich Miras is probably not a result of the 3DUP, but a result of the low mass-loss rate (which could be low because of 3DUP, see below). However, due to the small sample of AGB stars with observed dust spectrum and information on the Tc content, one must be cautious with strong conclusions.

### 3. Hypotheses for explanation

How can we interpret the two sequences? How do stars evolve in the  $K - [22]$  vs.  $P$  diagram? In Uttenthaler (2013), two main hypotheses were put forward.

- A Tc-poor Mira switches to the Tc-rich sequence upon a 3DUP event.
- Tc-poor and Tc-rich Miras are groups of different mass, i.e. the Tc-rich ones are more massive than the Tc-poor ones, and the two groups simply evolve differently in the diagram.

The first hypothesis offers two options: i) the pulsation period increases by the dredge-up of material (e.g. due to changed molecular opacities due to changed elemental abundances), and ii) the mass-loss properties ( $\dot{M}_{\text{dust}}$ , gas-to-dust ratio  $\delta$ , expansion velocity  $v_{\text{exp}}$ ) change such that the  $K - [22]$  color becomes bluer. A recent paper by Scholz et al. (2014) investigated the reaction of pulsation models on a moderate abundance change, e.g. due to 3DUP. They found that the pulsation period stays virtually unchanged by moderate abundance changes. If this is correct, then the first option of hypothesis 1 is excluded.

In Uttenthaler (2013), hypothesis 2 was favored as the correct explanation for the phenomenon. However, this conclusion was based on a premature analysis of the mean distance from the Galactic mid-plane of the two groups. The mean distance from the plane is an indicator of the mean mass of a class of stars, lower mean distance means higher average mass. It is known that long-period Miras are more massive than short-period Miras because on average they are closer to the Galactic mid-plane. The Tc-rich Miras are on average closer to the Galactic mid-plane than the Tc-poor Miras, suggesting that they have a higher mass. However, this is biased by the fact that Tc-rich Miras simply have longer periods on average. A closer inspection shows that in 50 d bins in the period range between 200 and 450 d, where the two groups overlap, both groups have essentially the same average distance from the plane! Hence, at a given period, Tc-poor and Tc-rich Miras have the same average mass.

Another indicator of the stellar mass could be the pulsation amplitude. More massive stars are expected to have a smaller pulsation amplitude. For our sample we inspected the amplitude in the V-band. We find that there is no significant difference in the pulsation amplitude of Tc-poor and Tc-rich Miras of spectral type M, MS, and S. Only the C-type Miras have clearly lower amplitudes because the molecules that have absorption bands in the visual range are much less temperature-sensitive in C-rich than in O-rich atmospheres. These pieces of evidence lead us to believe that hypothesis 2 is probably wrong, and that the second option offered by hypothesis 1, change in mass-loss properties by 3DUP, appears most likely to be the correct explanation for our observations.

Are there possible physical mechanisms with which we can understand a decrease of the (dust) mass-loss rate of a Mira upon 3DUP? It was suggested by Höfner (2008)

that scattering of photons off silicate grains of size  $\sim 1\mu\text{m}$  could be the driving mechanism of mass loss from oxygen-rich, M-type giants. This mechanism is successful in explaining the photometry of M-type giants (Bladh et al. 2013). We suggest here that the radioactivity of the material mixed to the surface during a 3DUP event could cause these large dust grains to dissolve again and thus decrease the mass-loss rate. Radioactively unstable isotopes may be integrated in the large dust grains, where they then decay. If the decay energy is deposited in the grain, it may be heated so much that it gets (partially) destroyed. Even a partial destruction could reduce the mass-loss rate already substantially because the scattering is most efficient at wavelengths of  $\sim 1\mu\text{m}$  where the maximum of the stellar flux is reached. Detailed calculations would be required to see if this hitherto unaccounted effect could be at work in the Tc-rich Miras.

#### 4. Application to bulge AGB stars

The separation of Tc-poor and Tc-rich Miras in Fig. 1 is so clear that it may actually be used to distinguish stars that did undergo a 3DUP event from those that did not. A line drawn between the points  $(P, K - [22]) = (120, 0)$  and  $(520, 4.2)$  separates the two sequences quite well: 85.4% of the Tc-poor Miras are above this line, while 87.2% of the Tc-rich ones are below, even without excluding the binary stars or any other special cases. This may be used to investigate the occurrence of 3DUP in stellar populations other than the solar neighborhood. Data were collected from Galactic bulge Miras via the MACHO survey (pulsation period), as well as photometry from 2MASS and WISE. The photometry was dereddened. In this data set of 1091 Miras, 82.9% of the stars are above the line defined above. This would mean that only a small number of Galactic bulge Miras undergoes 3DUP, consistent with the lack of C-stars in the bulge.

#### 5. Conclusions

We conclude that 3DUP appears to be doing something to the mass-loss properties of AGB variables, though we do not yet know how this is happening. This conundrum might teach us an important lesson about the mass-loss mechanism in O-rich Miras, which we better try to understand. Unfortunately, the author is a spare-time astronomer now, which limits the possibilities to investigate this phenomenon. Any support by interested researchers is warmly welcome!

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